

Depolarization characteristics of large-aperture neodymium glass slab laser amplifiers

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Based on a large-aperture neodymium glass photo-thermo-mechanical coupling model, this study systematically investigates depolarization characteristics under thermal, mechanical clamping, and coupled effects. The results demonstrate that thermal effects contribute significantly more to depolarization than purely mechanical clamping. The depolarization rate induced by lateral symmetric clamping increases nonlinearly with clamping torque, whereas front-side clamping structures substantially reduce local stress concentration, resulting in a lower depolarization and a more gradual increase with torque. Under thermo-mechanical coupling, constrained thermal expansion shear stress, leading to a pronounced nonlinear enhancement of the depolarization effect. Based on these mechanisms, we propose suppressing polarization by optimizing the clamping configuration and improving cooling uniformity. This work provides a theoretical foundation and practical engineering guidance for polarization stability control and the structural design of neodymium glass amplifiers in high-power laser systems.

Keywords: clamping structure, stress birefringence, neodymium glass, depolarization.

1. Introduction

High-power laser amplifiers have undergone rapid development in recent years. As the core gain medium in these systems, slab amplifiers are capable of amplifying seed light energy to the kilojoule level, with their performance directly determining the system's maximum output power. For instance, a single beamline at the National Ignition Facility (NIF) can achieve energies exceeding 20 kJ [1,2]. The ongoing pursuit of higher energy and repetition rates has driven the aperture size of slab lasers to exceed 400 mm, as exemplified by the 40 cm × 40 cm neodymium glass slabs employed in the NIF. However, large-aperture gain media are increasingly sensitive to stress. Stress-induced

birefringence resulting from both thermal effects and mechanical clamping significantly degrades the beam's polarization characteristics, presenting a critical bottleneck for further enhancement of system performance [3,4].

Research on depolarization mechanisms has historically centered on thermally induced effects. Inhomogeneous pumping creates temperature gradients within the neodymium glass, which in turn generate stress birefringence. This phenomenon of purely thermally induced depolarization has been extensively studied [5–8], leading to numerous proposed mitigation strategies. These primarily include the optimization of gain medium material properties [9–11], structural refinements of the gain medium itself [12], and the development of novel compensation techniques [13–15]. A common limitation of these studies, however, is the assumption that the gain medium exists in a free space, thereby neglecting the influence of mechanical clamping—a fundamental constraint in practical systems. Furthermore, the thermo-clamping coupling effect, a critical factor arising from constrained thermal expansion, remains inadequately investigated. Accounting for all depolarization sources is essential to preserve linear polarization in extreme environments like inertial confinement fusion (ICF) devices (*e.g.*, the NIF), where energy densities and laser intensities reach extreme levels. Although existing theoretical models and numerical methods have elucidated depolarization mechanisms within isolated physical fields [16–18], a comprehensive research framework integrating pure thermal, pure mechanical, and their coupled effects remain unestablished. Consequently, it is imperative to advance research in three key directions: the fundamental principles of thermally induced depolarization, the quantitative analysis of clamping-induced depolarization, and the underlying mechanisms of their coupled interactions. Progress in these areas will be pivotal for achieving polarization stability in high-power laser systems.

This study presents a systematic investigation of depolarization in large-aperture neodymium glass slab amplifiers under thermal, mechanical, and coupled thermo-mechanical effects. A multiphysics finite element model, integrating Jones matrix theory with thermo-mechanical coupling principles, is employed to quantitatively analyze the physical mechanisms of thermally induced depolarization, clamping-induced depolarization, and their synergistic interactions. The work aims to provide a theoretical foundation and practical design guidance for controlling polarization stability in high-power laser systems.

2. Theoretical models and methods

To investigate the depolarization characteristics of large-aperture neodymium glass amplifiers, a multiphysics analysis framework integrating thermal, mechanical, and optical effects was established. The governing equations and solution methods for the thermal field resulting from inhomogeneous pumping and the consequent stress field are well-established and are implemented as described in Reference [19]. By applying the principles of stress-induced birefringence and Jones matrix theory outlined in the

following sections, this study systematically quantifies depolarization under thermal, mechanical, and coupled thermo-mechanical loads.

When materials are subjected to stress, their original isotropic properties transform into anisotropic ones—a phenomenon known as the photoelastic effect. Under this effect, changes in a material's optical properties manifest as alterations in its inverse dielectric tensor $\mathbf{B}$. This tensor evolves from an initial constant value into a symmetric second-order tensor. A detailed formulation of this physical process is provided in Reference [20,21].

$$\begin{bmatrix} \Delta B_{11} \\ \Delta B_{22} \\ \Delta B_{33} \\ \Delta B_{23} \\ \Delta B_{13} \\ \Delta B_{12} \end{bmatrix} = \begin{bmatrix} B_{11} - B_0 \\ B_{22} - B_0 \\ B_{33} - B_0 \\ B_{23} \\ B_{13} \\ B_{12} \end{bmatrix} = \begin{bmatrix} \pi_{11} & \pi_{12} & \pi_{13} & 0 & 0 & 0 \\ \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0 \\ \pi_{13} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \pi_{44} \end{bmatrix} \cdot \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} \quad (1)$$

Among these parameters, n_0 is the initial refractive index of the material, σ is the second-order stress tensor, and π is the fourth-order photoelastic tensor. The components of the photoelastic tensor for neodymium glass at room temperature are provided in Table 1 [21].

The inverse dielectric tensor $\mathbf{B}$ can also be expressed as a 3×3 symmetric matrix, as shown below:

$$\mathbf{B} = \begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{12} & B_{22} & B_{23} \\ B_{13} & B_{23} & B_{33} \end{bmatrix} \quad (2)$$

For isotropic neodymium glass in the absence of external stress, its refractive index surface is spherical. When stress is applied, altering the relative dielectric impermeability tensor, this surface deforms into an ellipsoid, commonly referred to as the index ellipsoid. The mathematical expression for this ellipsoid is a second-order equation whose coefficients are determined by the components of the dielectric impermeability tensor [22].

$$B_{11}x^2 + B_{22}y^2 + B_{33}z^2 + 2B_{12}xy + 2B_{13}xz + 2B_{23}yz = 1 \quad (3)$$

For a horizontally polarized laser beam incident at the Brewster angle onto a slab laser amplifier made of neodymium glass, the transformation relationships between ΔB and $\Delta B'$ are respectively:

$$\Delta B' = A^T(\alpha) \cdot \Delta B \cdot A(\alpha) \quad (4)$$

In the above equation, where α is the coordinate rotation angle, the transformation matrix A is:

$$A(\alpha) = \begin{bmatrix} \cos \alpha & 0 & -\sin \alpha \\ 0 & 1 & 0 \\ \sin \alpha & 0 & \cos \alpha \end{bmatrix} \quad (5)$$

When a laser beam propagates along the z -axis, the birefringence characteristics at a given point are defined by the cross-section of the refractive index ellipsoid in the x - y plane, which forms an ellipse. The orientation of the principal optical axis θ , and the magnitudes of the refractive indices for the fast and slow axes, n_1 and n_2 are determined from the geometry of this ellipse.

$$\theta = \frac{1}{2} \arctan \left(\frac{2B_{12}}{B_{11} - B_{22}} \right) \quad (6)$$

$$n_{1,2}^2 = \frac{2}{(B_{11} + B_{22}) \mp \sqrt{4B_{12}^2 + (B_{11} - B_{22})^2}} \quad (7)$$

When a laser beam with wavelength λ passes through a birefringent medium of thickness d , a phase delay exists between the polarization components along the medium's fast axis and slow axis:

$$\varphi = \frac{2\pi}{\lambda} l_0 (n_1 - n_2) \quad (8)$$

Using the Jones matrix for calculation, it can be expressed as [23]. Here, l_0 represents the actual propagation distance of the light within the medium.

$$J = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} \exp(i\varphi_1) & 0 \\ 0 & \exp(i\varphi_2) \end{bmatrix} \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \quad (9)$$

Let the Jones matrix vector of the incident light be $E = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$, then the Jones vector of the incident light is:

$$E_1 = \begin{bmatrix} E_x \\ E_y \end{bmatrix} = J E_0 = \exp(i\varphi_1) \begin{bmatrix} \cos^2 \theta + \exp(i\varphi) \sin^2 \theta \\ \sin \theta \cos \theta - \exp(i\varphi) \sin \theta \cos \theta \end{bmatrix} \quad (10)$$

Depolarization is defined as the ratio of the y -component intensity to the total output intensity. This metric directly captures the portion of the initial x -polarized light that has been scattered into the orthogonal polarization state.

$$P = \frac{I_y}{I} = |E_y|^2 = \sin^2 \frac{\varphi}{2} \sin^2 2\theta \quad (11)$$

3. Results and discussion

3.1. Calculation results of thermal depolarization characteristics

Figure 1 presents a schematic of a xenon flashlamp-pumped neodymium glass laser amplifier. The gain module comprises three neodymium glass slabs alternated with two windows, with coolant channels between each optical component. Pulsed xenon lamps are positioned in parallel arrays on both sides of the module. The laser beam propagates parallel to the xenon lamps, sequentially passing through the following elements: a window, coolant, a neodymium glass slab, coolant, a second slab, coolant, a third slab, coolant, and the final window. The clear aperture of the neodymium glass is 400 mm within the physical slab dimensions of 810 mm × 460 mm. The material properties of the neodymium glass are provided in Table 1.

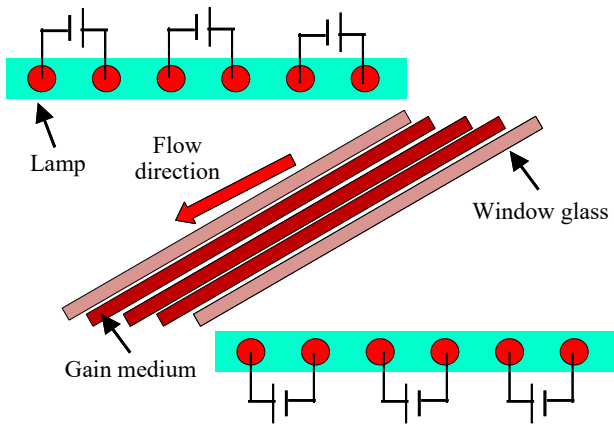


Fig. 1. Schematic diagram of xenon-doped neodymium glass laser amplifier [19].

T a b l e 1. Material and structural parameters of neodymium glass.

Properties	Value
Density ρ	2730 kg/m ³
Elastic module E	58.3 GPa
Poisson's ratio μ	0.26
Specific heat C_p	0.75 KJ/kg-K
Thermal conductivity k	0.59 W/m-K
Thermal expansion coefficient α	$116 \times 10^{-7} \text{ K}^{-1}$
Index of refraction $n_0(1053 \text{ nm})$	1.535
Stress-optic coefficients π_{11}	1.526 TPa ⁻¹
Stress-optic coefficients π_{12}	2.540 TPa ⁻¹
Stress-optic coefficients π_{44}	2.033 TPa ⁻¹

Figure 2 shows the three-dimensional thermal source distribution of neodymium glass after pumping. In the theoretical simulation, the xenon lamp pump employed typical operating parameters of a pulse width of 300 μs and a repetition frequency of 1 Hz. Spatially, the symmetric arrangement of the xenon flashlamps on both sides of the slab results in a non-uniform energy deposition profile. This leads to significant regional variations in pump intensity and the resultant heat generation. A cross-sectional analysis of the thermal distribution reveals a pronounced attenuation of the heat source along the thickness of the neodymium glass. This finding provides critical input data for subsequent analyses of thermally induced stress and depolarization. The model accurately captures the nonlinear attenuation of light intensity at the medium boundary and the modulation of the heat deposition pattern by the slab's geometry.

In this study, the maximum heat generation of neodymium glass is $2.02 \times 10^5 \text{ W/cm}^3$, with a convective heat transfer coefficient of $18000 \text{ W/(m}^2 \cdot \text{K)}$ for both surfaces of the

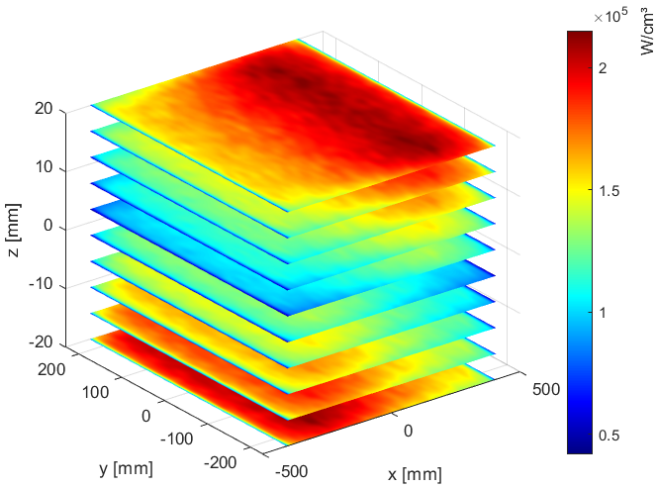


Fig. 2. Three-dimensional thermal source distribution in neodymium glass after pumping.

Type: Temperature
Unit: K
Time: 300 s

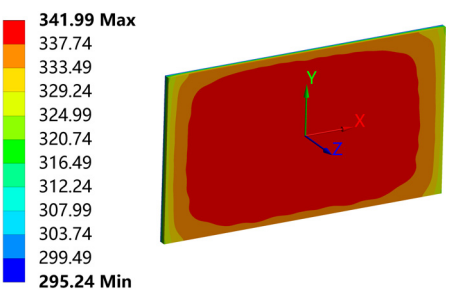


Fig. 3. Temperature distribution of the steady-state cross-section in neodymium glass.

neodymium glass slab. The steady-state temperature distribution after 300 seconds is shown in Fig. 3. The results reveal a pronounced cross-sectional temperature gradient, with the highest temperature of 341.99 K located in the central region and the lowest temperature of 295.24 K at the edges, yielding a maximum temperature difference of 46.75 K. The overall distribution exhibits a “high-center, low-edge” gradient structure, a pattern determined by the thermal conductivity of the neodymium glass and the boundary cooling conditions. A distinct thermal boundary layer is evident between the high-temperature central zone and the low-temperature periphery. The concentration of thermal stress in this transition region is likely to significantly impact the material’s structural stability.

Figure 4 illustrates the thermal stress distribution in the neodymium glass under xenon lamp pumping and the resulting depolarization. Figure 4(a) and (b) show the principal stress distributions along the x and y directions, respectively, both exhibiting symmetry with elevated stress magnitudes near the edges. Figure 4(c) presents the in-plane shear stress, whose distribution corresponds closely with the depolarization pattern shown in Fig. 4(d). This correlation is particularly evident in the four corner regions. The morphology of the calculated depolarization distribution in this work is consistent with that reported in Reference [19], a result primarily attributed to the identical xenon flashlamp pumping configuration. However, due to the larger aperture and

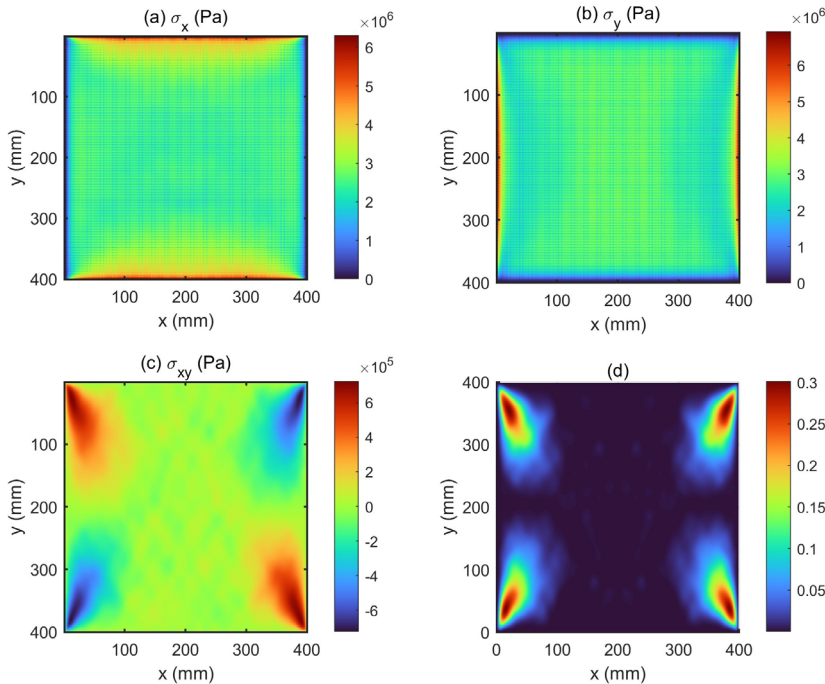


Fig. 4. Stress and depolarization distributions in neodymium glass under thermal (a) principal stress in the x -direction, (b) principal stress in the y -direction, (c) shear stress in the xy -plane, and (d) depolarization image.

greater thickness of the neodymium glass slab used in this study, the thermal accumulation effect is more pronounced, leading to a maximum depolarization rate of 30.12%, which is consistent with the stress-induced birefringence model. This model states that shear stresses alter the local refractive index, causing a non-uniform phase shift that modifies the polarization state of the transmitted light. Therefore, the spatial pattern of depolarization directly maps the thermal stress gradients, confirming that stress birefringence is the primary mechanism for thermally induced depolarization.

3.2. Calculation results of clamping depolarization characteristics

Figure 5 illustrates the clamping configuration and force application schematic for the large-aperture neodymium glass assembly. The neodymium glass slab has dimensions of 810 mm × 460 mm × 40 mm, and its material properties are listed in Table 1. The clamping is achieved by three set screws on each lateral side and nine set screws on the front face. The slab is positioned at the center of the assembly, where external loads F are applied to the front and side surfaces, simulating the forces from the set screws. The actual apparatus incorporates auxiliary structures, such as a frame and a mounting bracket (simplified in the schematic), which provide rigid support and ensure the positional accuracy of the set screws, respectively. This schematic clearly delineates the force transmission path—from the slab to the set screws and, finally, to the clamping structure—thereby establishing a foundation for subsequent analysis of the mechanical and optical behavior of the neodymium glass under complex clamping conditions.

Figure 6 shows the stress distribution and the corresponding spatial distribution of the depolarization rate in neodymium glass under a laterally symmetric clamping condition with a torque of 10 cN·m. The results indicate that the principal stress in the x -direction features an alternating pattern of compressive and tensile regions, with the maximum compressive stress localized near the clamping points. The principal stress gradient in the y -direction undergoes significant variation, revealing a strong trans-

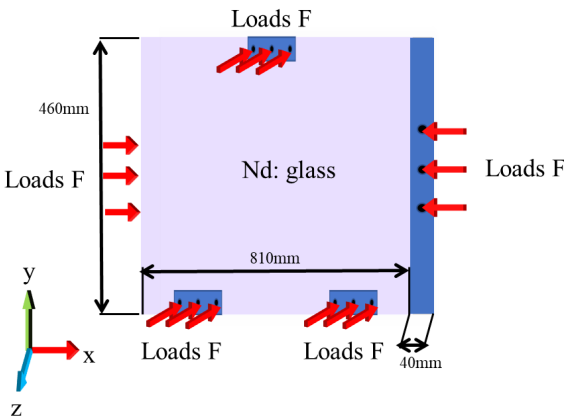


Fig. 5. Schematic of the clamping force application on a large-aperture neodymium glass assembly.

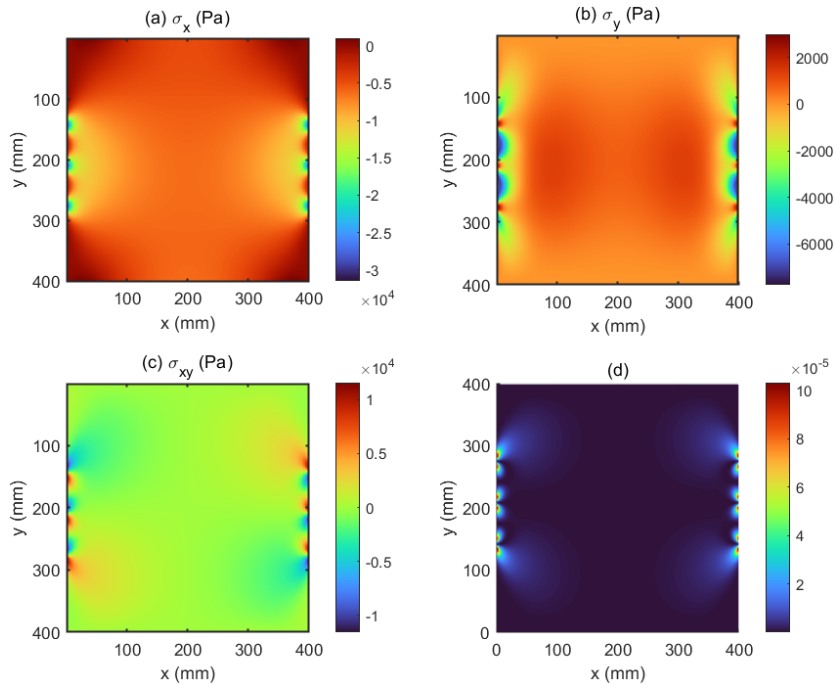


Fig. 6. Stress and depolarization distributions in neodymium glass under symmetrical side-clamping. (a) Principal stress in the x -direction, (b) principal stress in the y -direction, (c) shear stress in the xy -plane, and (d) depolarization image.

verse constraint effect. The shear stress τ_{xy} forms symmetrical vortex-like distributions at the edges of the clamping zone, which is the key mechanical driver for the elevated depolarization. Figure 6(d) shows the resulting depolarization rate distribution. Areas of high depolarization coincide spatially with the regions of peak shear stress, confirming the dominant role of the photoelastic effect. The depolarization rate approaches zero in low-stress zones, which is consistent with theoretical predictions. This clear correlation provides direct guidance for the subsequent optimization of the clamping design.

Figure 7 illustrates the relationship between the depolarization rate of neodymium glass and the applied clamping torque under symmetrical clamping conditions. Simulations were conducted for five clamping torques ranging from 10 to 70 $\text{cN}\cdot\text{m}$, and the resulting data were fitted with a smooth curve. The figure reveals a nonlinear growth trend, characterized by a slow increase in the low-torque range and a more rapid acceleration in the high-torque range. When the clamping torque increases from 10 to 30 $\text{cN}\cdot\text{m}$, the depolarization rate rises only from 0.0103% to 0.0929%, indicating a threshold effect in the low-stress regime. However, once the clamping torque exceeds 50 $\text{cN}\cdot\text{m}$, the rate of increase accelerates significantly, demonstrating that the stress-induced birefringence effect is highly sensitive to high stress levels.

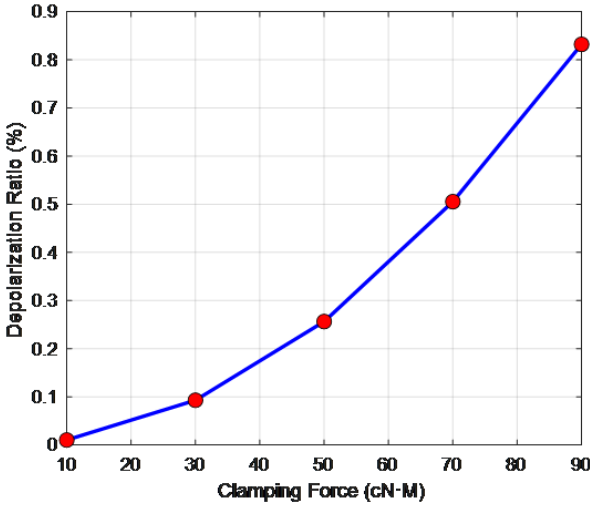


Fig. 7. The relationship between the depolarization rate of neodymium glass and the clamping force under symmetrical lateral clamping.

This study further simulated the stress distribution and depolarization characteristics of neodymium glass under front-clamping conditions. The clamping load was applied via nine front-mounted set screws, as shown in Fig. 8, with a torque range of 10–90 cN·m. Figure 8(a) shows the spatial distribution of the depolarization rate within the neodymium glass under a clamping torque of 10 cN·m. Regions of high depolarization are localized near the clamping points and edges, exhibiting distinct stress concentration, with a maximum depolarization rate of 0.00037%. Figure 8(b) quantitatively illustrates the relationship between the depolarization rate and clamping torque: within the low-torque range (10–30 cN·m), the depolarization rate increases

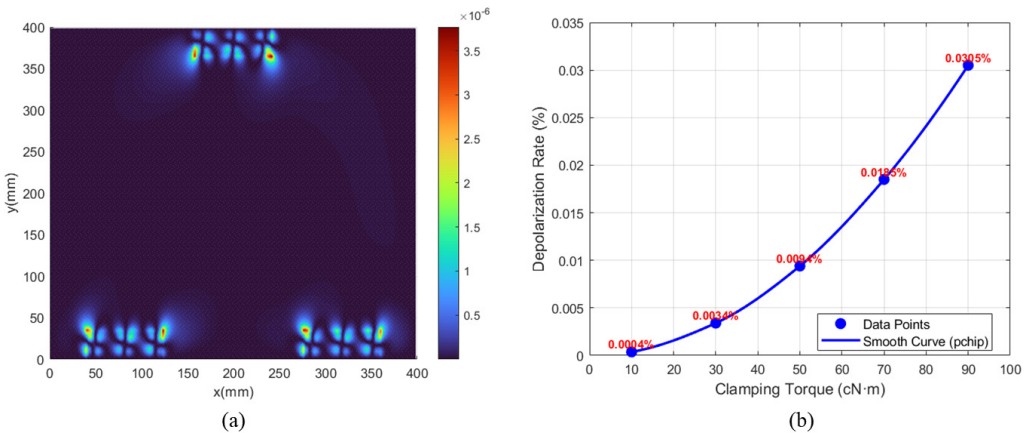


Fig. 8. (a) Depolarization distribution in neodymium glass under front-side clamping. (b) Depolarization rate as a function of clamping torque under front-side clamping.

slowly, indicating a stress threshold effect. However, when the clamping torque exceeds $50 \text{ cN}\cdot\text{m}$, the depolarization rate rises sharply, exhibiting an approximately linear growth trend, which suggests the stress-induced birefringence effect has entered a sensitive regime. The maximum depolarization rate under the front-clamping configuration is significantly lower than that of traditional side-clamping. Under an identical clamping torque of $50 \text{ cN}\cdot\text{m}$, front clamping results in a depolarization rate of 0.0095% , whereas side clamping produces a rate as high as 0.5% . This disparity originates from fundamentally different stress distribution mechanisms: front clamping applies a more uniform pressure over a larger area, effectively mitigating localized stress concentration and, crucially, the shear stress components that drive birefringence. Consequently, front clamping offers superior performance in both mechanical stability and the preservation of optical quality, making it particularly suitable for high-power laser systems with stringent polarization requirements.

3.3. Depolarization under thermo-mechanical coupling

The preceding analysis separately elucidated the individual effects of thermal and clamping stress on the depolarization characteristics of neodymium glass. However, in operational high-power laser systems, the gain medium is simultaneously subjected to pump-induced thermal loading and mechanical clamping constraints. The nonlinear

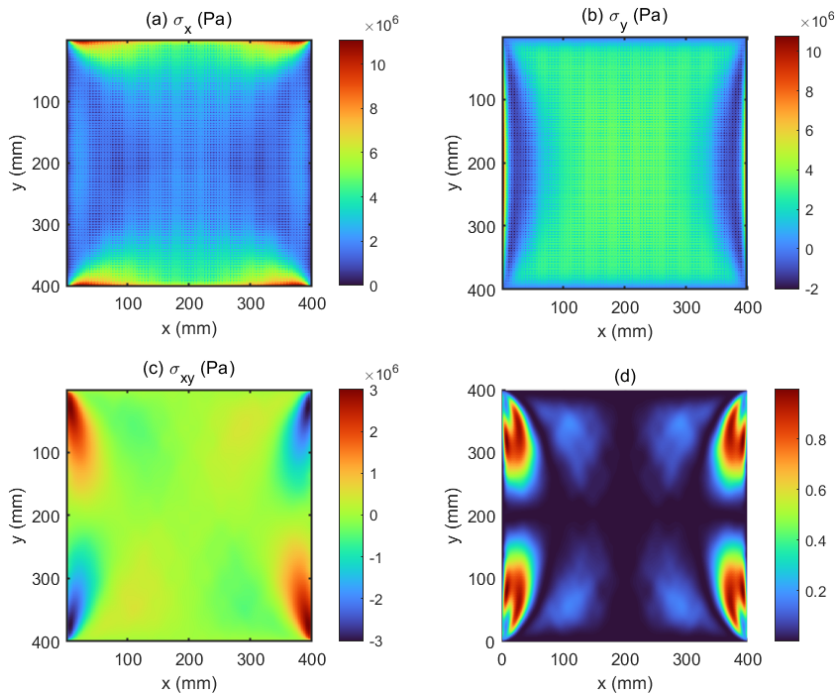


Fig. 9. Depolarization under thermo-mechanical coupling. (a) Principal stress in the x-direction, (b) principal stress in the y-direction, (c) shear stress in the xy-plane, and (d) depolarization image.

coupling between these factors may cause the resultant depolarization to deviate significantly from a simple linear superposition of the individual effects. This section, therefore, investigates the spatial distribution and physical mechanisms of depolarization under the combined thermo-mechanical load, aiming to reveal the synergistic modulation of the polarization state within the composite stress field.

Based on the previously established thermo-mechanical coupling model, both the pump light heat source and a symmetrical clamping load were applied to the neodymium glass finite element model. The resulting spatial distribution of the depolarization rate, calculated via the Jones matrix method, is shown in Fig. 9. The thermal boundary conditions were identical to those in Section 3.1, with a clamping torque of 10 cN·m. The nonlinear coupling exhibits distinct characteristics: in the central region, thermally induced depolarization dominates, presenting a symmetrical gradient distribution, whereas in the peripheral clamping zones, mechanical stress significantly amplifies local depolarization, forming pronounced bands of stress concentration. Critically, the overall magnitude of the depolarization field under this coupled load far exceeds the linear sum of the isolated thermal and mechanical effects. This nonlinear enhancement is attributed to a substantial increase in the in-plane shear stress caused by constrained thermal expansion. This finding confirms the theoretical prediction that thermo-mechanical coupling significantly exacerbates depolarization, providing critical insight for designing subsequent compensation strategies.

4. Conclusions

This study employs a multiphysics-coupled finite element model to systematically investigate the stress-induced birefringence characteristics of large-aperture neodymium-doped glass slab amplifiers under thermal loads, mechanical clamping, and thermo-mechanical coupling. The results indicate that under identical conditions, the birefringence induced by thermal effects alone is significantly greater than that from mechanical clamping alone. A comparison between side-symmetric and front-side clamping structures shows that the birefringence increases approximately linearly with clamping torque, with front-side clamping producing a markedly lower effect than side clamping. Under thermo-mechanical coupling, constrained thermal expansion significantly enhances in-plane shear stress, leading to a nonlinear increase in the depolarization rate, which can reach up to 99%. To mitigate this coupled depolarization, we recommend optimizing the clamping design—for instance, by integrating front-end clamping with flexible supports—and enhancing cooling uniformity to reduce the thermo-mechanical coupling intensity. This work provides a theoretical foundation and engineering guidance for the multiphysics co-design and polarization stability control of neodymium glass amplifiers in high-power laser systems.

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